Developing Methods and Techniques for System of Systems Engineering

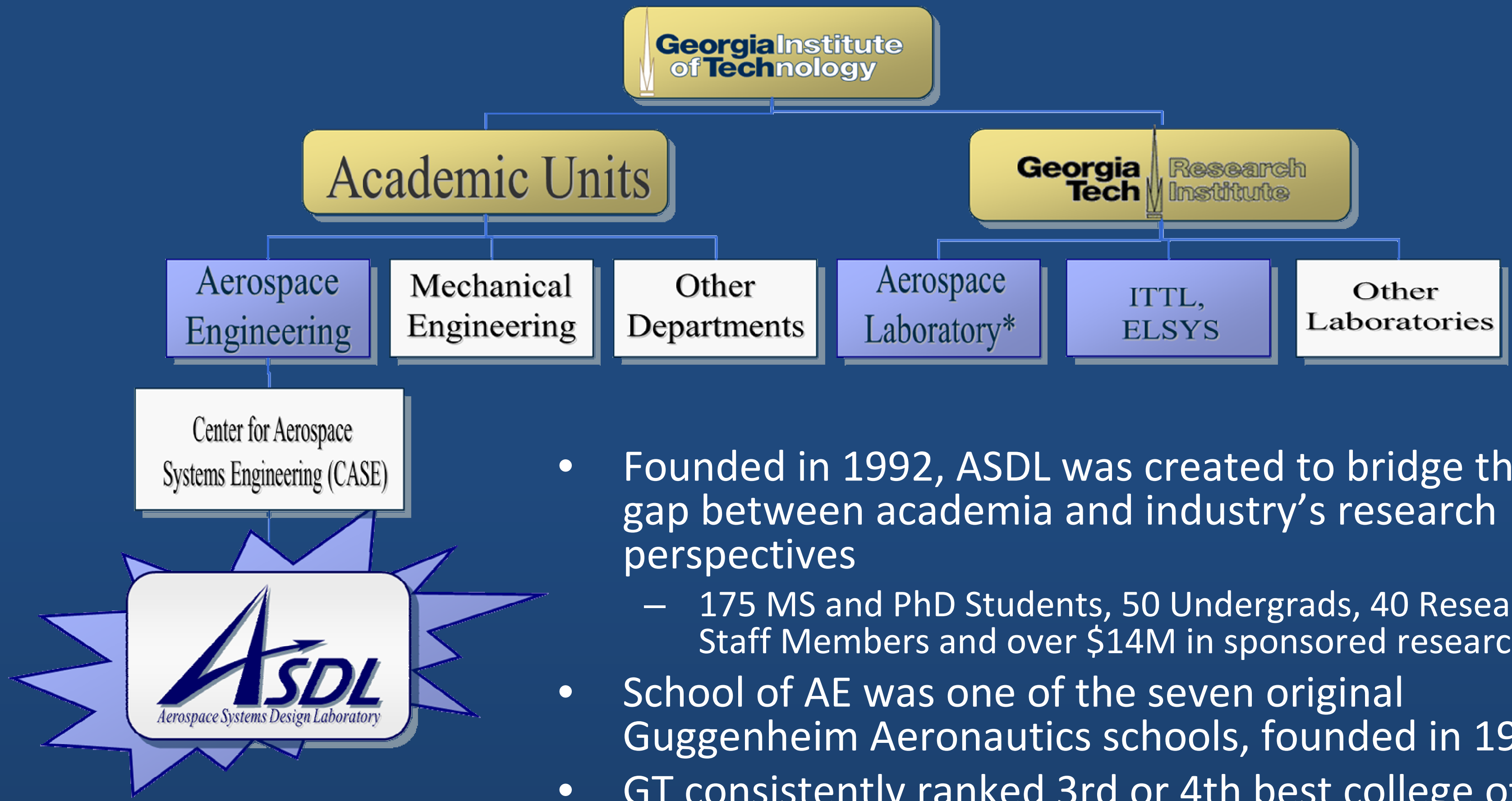
Presented
By

Dr. Dimitri Mavris
Boeing Professor for Advanced Aerospace Systems Analysis
Director, Aerospace Systems Design Laboratory (ASDL)
Georgia Institute of Technology
dimitri.mavris@ae.gatech.edu

Outline

- Motivation
- What is a SoS, and what is SoSE?
- Challenges in SoSE
- Enabling Techniques and Methods
- Research Areas
- Conclusions

The Aerospace Systems Design Laboratory



- Founded in 1992, ASDL was created to bridge the gap between academia and industry's research perspectives
  - 175 MS and PhD Students, 50 Undergrads, 40 Research Staff Members and over $14M in sponsored research
- School of AE was one of the seven original Guggenheim Aeronautics schools, founded in 1930
- GT consistently ranked 3rd or 4th best college of engineering in the country based on US News & World Report

* Aerospace, Transportation & Advanced Systems Laboratory

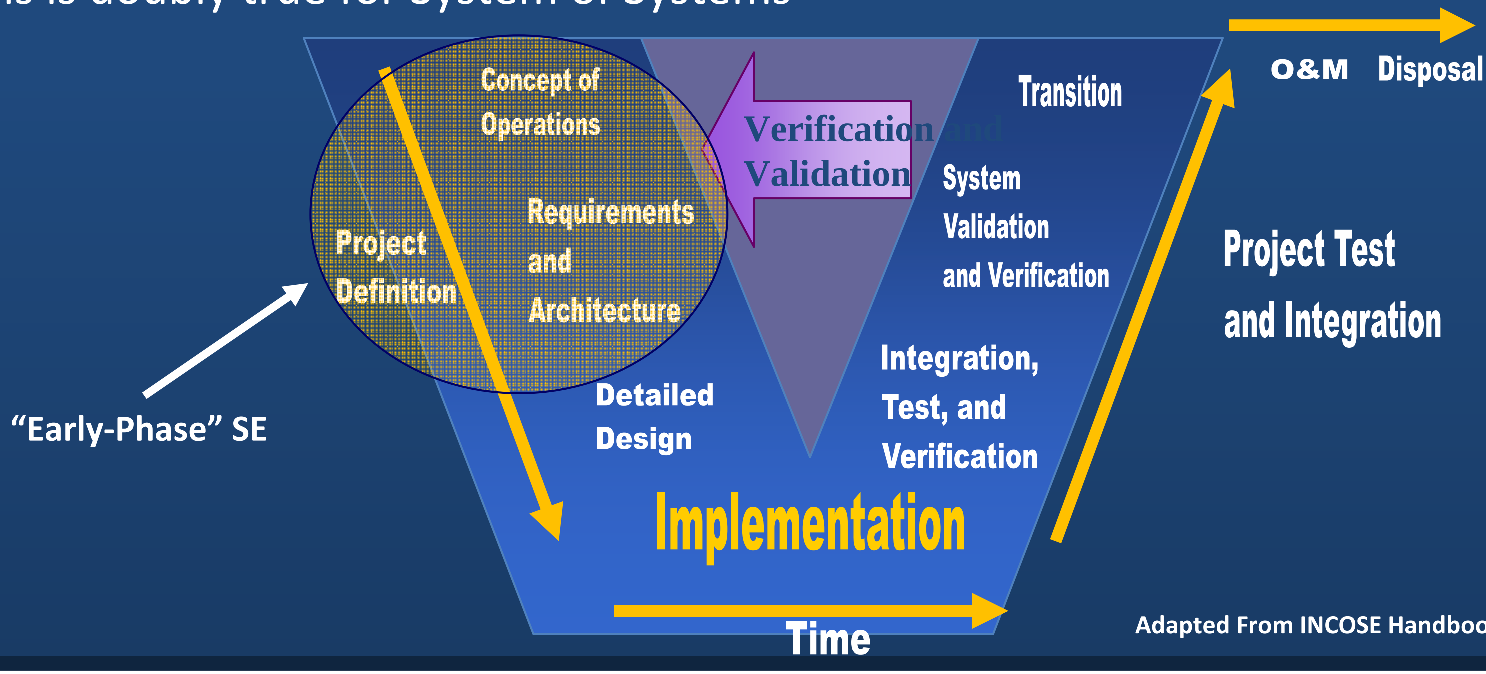
Motivation - Increasing need for more interoperable, cost-effective systems

- Military systems are becoming *increasingly complex* as information and communications technology surges
- Distribution of operations is creating a need for aerospace systems to become *increasingly interoperable*
- Despite their complexity, aerospace systems must be *cost effective*

These trends have resulted in an increased focus on *System-of-Systems Engineering* in civil, military, and space applications

Motivation- Emphasis on “Early-Phase” SE

- Systems Engineering (SE)
  - **An *interdisciplinary* approach to *derive, evolve, and verify* a life-cycle balanced *system solution* that *satisfies customer expectations* and meets public acceptability (IEEE 1220-1994)**
- The most fundamental (and most difficult and costly to reverse) decisions are made in the early phases of design and architecture definition
  - This is doubly true for System of Systems



Adapted From INCOSE Handbook

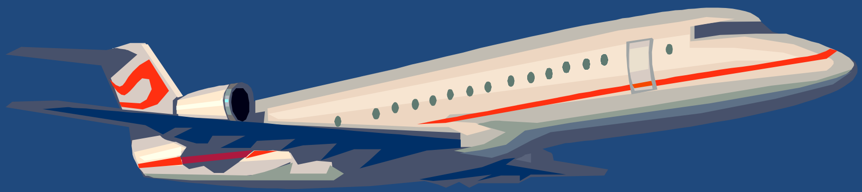
Shift to a "Capability-based" Focus

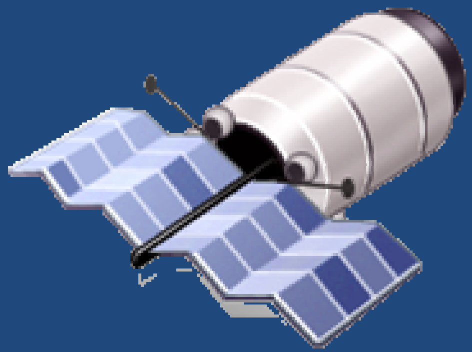
"In the past 15 years, the Department of Defense (DOD) has faced a constant stream of new challenges…the United States must be prepared both to deal with a larger number of more diverse threats with varied attributes and to do so in circumstances involving complex and uncertain risks."

-*Naval Analytical Capabilities: Improving Capabilities-Based Planning,* Committee on Naval Analytical Capabilities and Improving Capabilities-Based Planning, National Research Council

- There is an overall desire to acquire capabilities, particularly in military applications
  - New acquisition paradigms attempt to be more "top-down" and avoid stove-piping
- These capabilities are often not enabled by a single system, but rather by a system of systems
  - The supporting systems (such as ships and aircraft) are typically multi-mission
  - Systems cannot be studied in isolation, but must be examined in the context of operational scenarios, environments, and interactions
- High-quality System of Systems Engineering is a key component to successful capability-based design

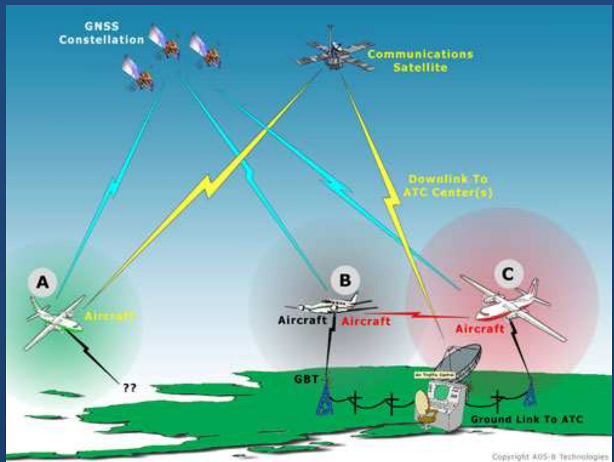
What is a system?

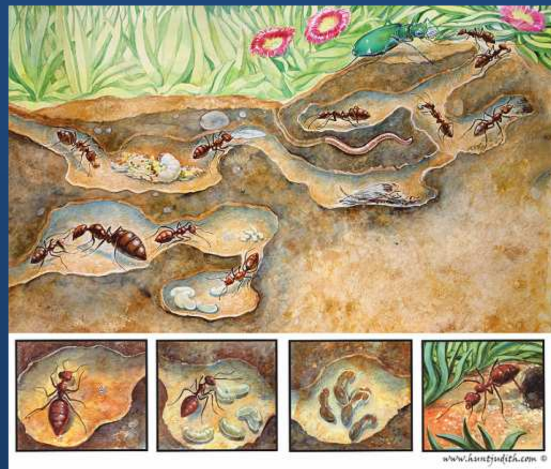




"A set of functional elements organized to satisfy user needs." (IEEE P1220 p. 238)

What is a System of Systems?





System of Systems

- "A set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities."
  - DoD Defense Acquisition Guidebook 2004

- "System of systems applies to a system-of-interest whose system elements are themselves systems; typically these entail large scale inter-disciplinary problems with multiple, heterogeneous, distributed systems."
  - INCOSE-TP-2003-002-03, Systems Engineering Handbook V3

- "Groups of systems, each of which individually provides its own mission capability, that can be operated collectively to achieve an independent, and usually larger, common mission capability "
  - Pre-Milestone A and Early-Phase Systems Engineering: A Retrospective Review and Benefits for Future Air Force Systems Acquisition. National Academies Press, 2008

What makes Systems of Systems (SoS) Different?

- Compared to a System, an SoS might:
  - Be larger in scope
  - Have more complex integration
  - Usually be subject to higher degree of uncertainty and risk
  - Evolve more continuously with elements of differing lifecycles
  - Lack a single management/acquisition entity and have a broader range of stakeholders
  - Have elements which are not designed to fit the whole, and which are integrated post-design and deployment
  - Exhibit emergent behaviors
  - Have more ambiguous requirements and fuzzy boundaries
  - Have continuous SE which is never finished

System-of-Systems Engineering is an emerging discipline in the aerospace community and new methods and techniques are required to address SoS challenges, but these should be based on proven Systems Engineering methods

What is SoSE?

- System of Systems (SoS) Engineering is an emerging interdisciplinary approach focusing on the effort required to transform capabilities into SoS solutions and shape the requirements for systems. SoS Engineering ensures that:
  - Individually developed, managed, and operated systems function as autonomous constituents of one or more SoS and provide appropriate functional capabilities to each of those SoS
  - Political, financial, legal, technical, social, operational, and organizational factors, including the stakeholders' perspectives and relationships, are considered in SoS development, management, and operations
  - A SoS can accommodate changes to its conceptual, functional, physical, and temporal boundaries without negative impacts on its management and operations
  - A SoS collective behavior, and its dynamic interactions with its environment to adapt and respond, enables the SoS to meet or exceed the required capability.

Source: System of Systems Engineering Center of Excellence, Sponsored by the Office of the Under Secretary of Defense for Acquisition, Technology, & Logistics, Defense Systems, Systems and Mission Integration, Joint Force Integration (USD-AT&L)

INCOSE Challenges in SoS Engineering

1. Complexity is a major issue
2. Management can overshadow engineering
3. The initial requirements are likely to be ambiguous
4. System elements operate independently
5. Fuzzy boundaries cause confusion
6. System elements have different life cycles
7. SoS engineering is never finished

New methods and techniques are required to address these challenges

The Evolution of New Ideas

"All truth passes through three stages. First, it is ridiculed. Second, it is violently opposed. Third, it is accepted as being self-evident."

--Arthur Schopenhauer, German philosopher (1788 - 1860)

This principle is observed for all new ideas as well

Overcoming Organizational Barriers associated with any new Methodology

- New methods go against the grain of established paradigms that are well defined and accepted by the practicing community and thus are always viewed with skepticism, criticism, or cynicism

- Criteria to facilitate the introduction and acceptance of new methods :
  - The underlying theories, methods, mathematics, logic, algorithms, etc. upon which the new approaches are based must be well understood, accepted, scientifically sound and practical
  - Familiarity is needed with the underlying theories and the material needed for someone to understand the method itself must be readily available
  - Availability of training material written on the overarching method, tutorials, etc. with relevant examples
  - Tools automating the proposed method and making it practical for every day use to take the method beyond the academic level
  - Relevant examples and applications within a given field of study

  - Proposed methods which are grounded in or are complimentary to established practices have a better chance of succeeding

What is needed for this New Paradigm Shift to Occur?

- Transition from single-discipline to multi-disciplinary analysis, design and optimization that can handle concurrently *means* and *ways* trades
- Easy to use integrative environments that can handle the combinatorial nature of the SOS problems
- Automation of the resultant integrated design process
- Transition from a reliance on historical data to physics-based formulations, especially true for unconventional concepts
- Means to perform requirements exploration, technology infusion trade-offs and concept down selections during the early design phases (conceptual design) using physics-based methods
- Methods which will allow us to move from deterministic, serial, single-point solutions to dynamic parametric trade environments
- Incorporation of probabilistic methods to quantify, assess risk
- Transition from single-objective to multi-objective optimization
- Need to speed up computation to allow for the inclusion of variable fidelity tools so as to improve accuracy, from macro-level to meso- to micro-level representations
- Means to facilitate data and knowledge creation, storage, versioning, retrieval and mining
- An integrated knowledge based systems engineering and management framework
- Means to perform dynamic visualization of the results in a team-centered, real-time analysis environment

Synthesis of Established Techniques to Create New Methods

Established Techniques

- Response Surface Methodology *(Biology, Operations Research)*
- Neural Networks *(Artificial Intelligence, Image Processing)*
- Design of Experiments *(Agriculture, Manufacturing)*
- Design for Computer Simulation *(Geo-statistics, Physics, Nuclear)*
- Quality Function Deployment, Pugh Diagram *(Automotive, Electronics)*
- Morphological Matrix or Matrix of Alternatives *(Forecasting)*
- Multi-attribute decision making (MADM) techniques *(U.S Army, DoD)*
- Uncertainty/Risk Analysis *(Control Theory, Finance, Mathematics)*
- Agent based Models, System Dynamics, Network Theory *(Business, Entertainment, etc.)*
- Visual Analytics *(Homeland Security, Visualization, Video Gaming)*

Customized Methods Synthesized from Established Techniques

- Feasibility/Viability Identification
- Robust Design Simulation (RDS)
- Technology Identification, Evaluation, Selection (TIES)
- Joint Probabilistic Decision Making (JPDM)
- Unified Trade-off Environment (UTE)
- Inverse Design using Filtered Monte Carlo Simulation
- The Architecture-based Technology Evaluation and Capability Tradeoff (ARCHITECT)

An Architecture-based Approach to SoSE

- "*The initial stages of architecture design are where the most fundamental design decisions are made*; these are the decisions which are most difficult to correct when they are in error"
  - Felix Bachmann, Software Engineering Institute (SEI) at Carnegie Melon

- "To *effectively acquire complex systems-of-systems in a capability-based acquisition environment requires that we increase the use of integrated architectures* to identify inter-relationships and resolve issues with system integration and interoperability that impact the operational effectiveness of warriors; platforms; command and control; networks; and weapons."
  - Phillipp Charles, Chief Engineer of SPAWAR Systems Center

- "Degradation in combat effectiveness can be caused by…poor or non-existent integration or interoperability. Because integration and interoperability are so critical to combat effectiveness, *the entire Family of Systems must be considered in the engineering and acquisition process if decision makers are to choose the most operationally sound, technically feasible, and effective program investments*"
  - Dickerson, Soules, Sabins, Charles in "Using Architectures for Research Development and Acquisition"

Architecture

Historically:

- The art or practice of designing and constructing buildings (Oxford English Dictionary)
- Formation or construction resulting from or as if from a conscious act resulting in a unifying or coherent form or structure (Merriam-Webster Dictionary)
- Many others
- Common Themes: Structure, Utility, Beauty (or attractiveness)

In Systems Engineering:

- The fundamental organization of a system, embodied in its components, their relationships to each other and the environment, and the principles governing its design and evolution. (From ANSI/IEEE 1471-2000)

At ASDL:

- The fundamental organization of a system, embodied in its components, their relationships to each other and the environment, the principles governing its design and evolution, its purpose (utility), and its attractiveness (e.g. functionality, cost, etc)

Including the utility and the value into the architecture development phase requires the ability to estimate and evaluate these components of the architecture, thus driving a need for architecture frameworks to be integrated with systems engineering and modeling and simulation

The System Alternative Space

- The Interactive Reconfigurable Matrix of Alternatives (IRMA) is used to explore the alternative space for a new system
- The IRMA is demonstrated here using a notional example

Interactive Reconfigurable Matrix of Alternatives (IRMA)

Engagement Model Inputs

							TOPSIS
Platform	Presets	B-52	B-1B	B-2	F-16 (Yes)	F/A-18E	
		F/A-22	New Design				
	Cruise Speed	Subsonic	Supersonic	Hypersonic	Orbital		
	Engine Type	Turbofan	Turbojet	Ramjet	Turboramjet	Scramjet	
		Pulse Detonation	Combined Cycle	Other			
	Number of Engines	1	2	4	Other		
	Ferry Range	<1000 nm	1000-3000nm	3000-5000 nm	>5000 nm		
	Refuelable	Yes	No				
	Piloting	Manned	Unmanned/Remote	Unmanned/Autonomous			
	Stores	External	Internal Exposed	Internal Enclosed			
	Wing Morphing	None	Variable Sweep	Variable Camber			
	Body Style	Blended Wing	Flying Wing	Conventional			
Missile	Presets	Air Launched Tomahawk	JASSM (Yes)	ASDL Parametric Model	Traditional ICBM	New Design	
	Primary Engine Type	Turbofan	Turbojet	Ramjet	Turboramjet	Scramjet	
		Rocket	Airbreathing Rocket	Pulse Detonation	Combined Cycle	Other	
	Inlet Position	Chin	Nose	Bottom	Top	Twin Offset	
		Twin Symmetric	None				
	Flight Speed	Subsonic	Supersonic	Hypersonic	Orbital		
	Range	< 300nm	300-600nm	600-1200 nm	>1200 nm		
	Wings	Subsonic Wings	Supersonic Wings	Hypersonic Wings	None		
	Trajectory	Terrain Following	Low Altitude	High Altitude	Climb and Glide	Ballistic	
	Controls	Tail	Canard	Thrust Vectoring	Other		
	Seeker/Guidance	Laser	Infrared	RADAR	GPS	INS	
Missile Engine	Number of Spools	1	2 (No)	None			
	Compressor Style	Axial (No)	Centrifugal	None			
	Nozzle Type	Converging	Converging-Diverging	Variable			
	Blade Fabrication	Equiax	Directionally Solidified	Single Crystal	Other	N/A	
	High-Temp Material	Titanium	Nickel-Alloy	Carbon Composites	Metal Composites	Ceramic Composites	
	Cooling Scheme	Convection	Impingement	Film	Transpiration	Liquid	

Possible Combinations

1,500

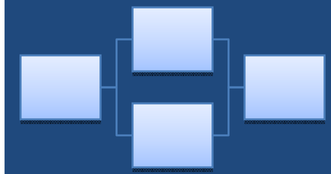
Computational Analysis Time

One Run per Second:	0.02 Days
One Run per Minute:	1.04 Days
One Run per Hour:	62.50 Days

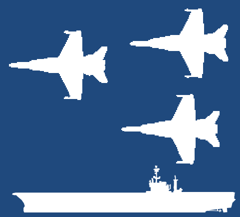
Minimum TRL: 1

Air Force Asset Only: No

SoS Architecture Alternative Space

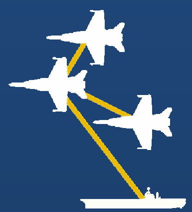


- Operational Alternatives (HOW and WHEN)
  - Changing the ways things are done (for example, the communication structure, or the order in which activities are performed)



- System Alternatives (WHAT and HOW MANY)
  - Changing the elements (physical systems, the means) of the architecture

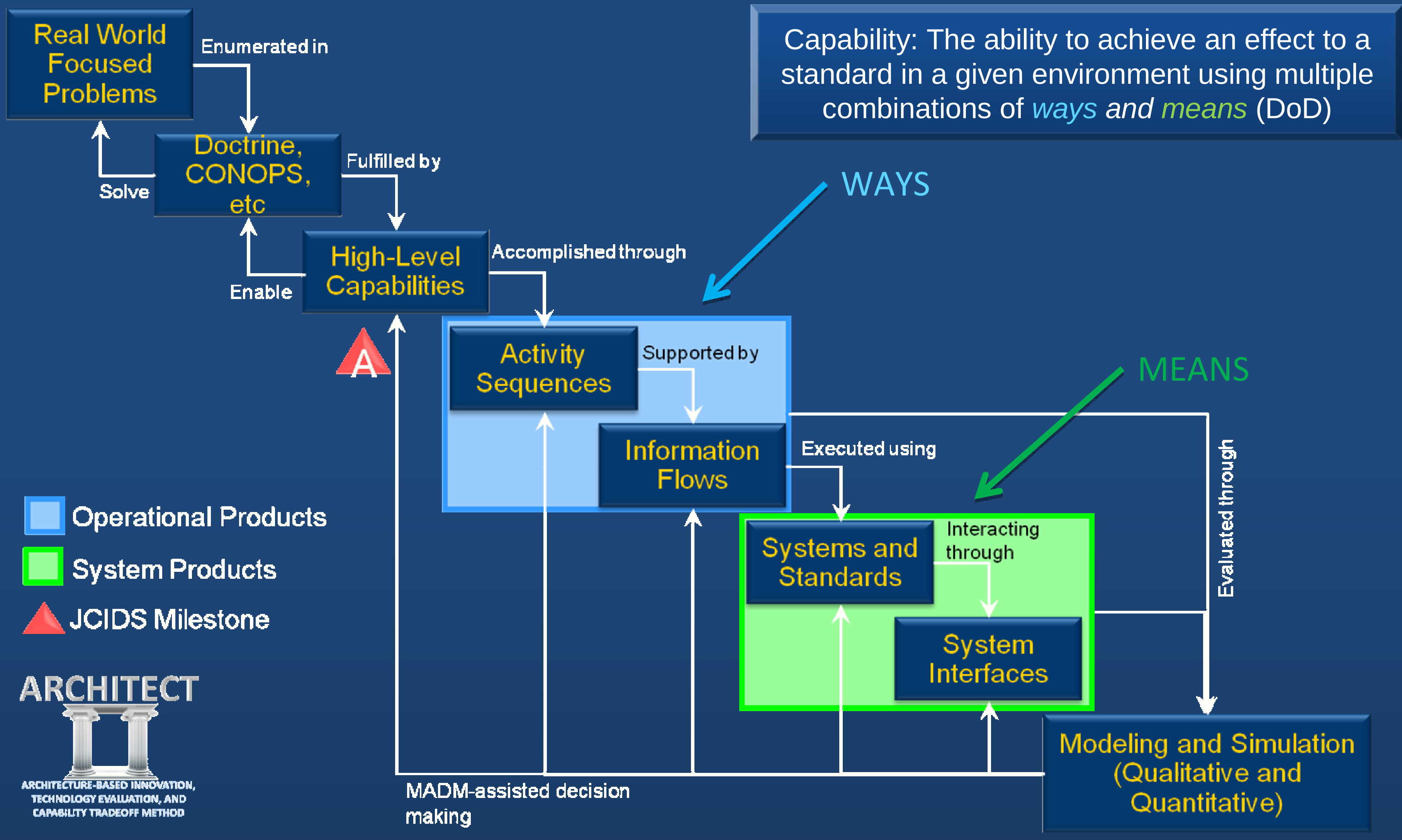
- Organizational Alternatives (WHO)
  - Changing who is responsible for certain elements, activities, facilities, etc



- Network Alternatives (HOW)
  - Changing the network architecture that enables the information flow required by the SoS

- Combinations of the above

The Architecture-based Technology Evaluation and Capability Tradeoff Method (ARCHITECT)

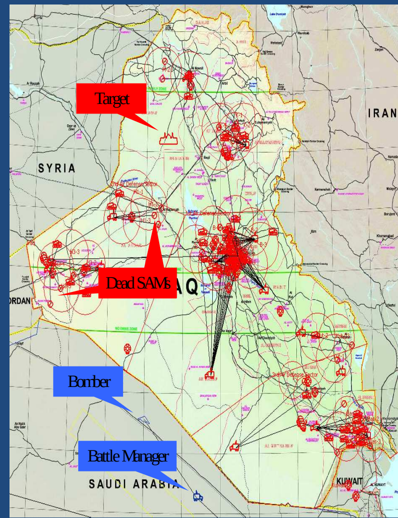


Modeling and Simulation Challenges in SoS Engineering

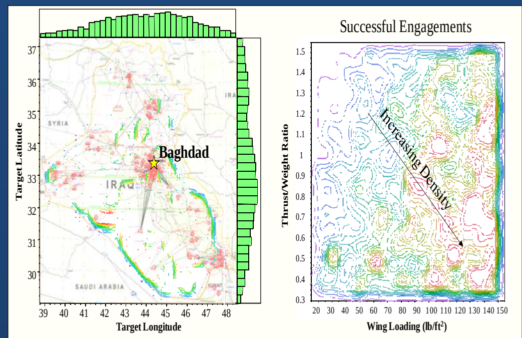
- Physical experiments are typically infeasible or limited
  - Computer simulations are required, and are often computationally intensive and time consuming
  - Verification and Validation is a challenge
- SoS are complex
  - Limits available modeling techniques
  - Often results in high dimensionality
- SoS have a large and diverse alternative space
  - Unfathomable number of combinations
  - Need to speed up modeling and simulation
  - Can be challenging to visualize results
- SoS are stochastic in nature
  - For a given set of inputs, the results are a distribution
  - Behavior is often modal in nature

Extension to Systems-of-Systems Analysis

- The DoD shift to capability-based acquisition is merging the operations research and systems design communities
- The impact of systems and sub-systems is often negligible when compared to tactics, doctrine, and strategy
- Methods for efficient scenario construction, surrogate creation, and optimization for SoS are needed

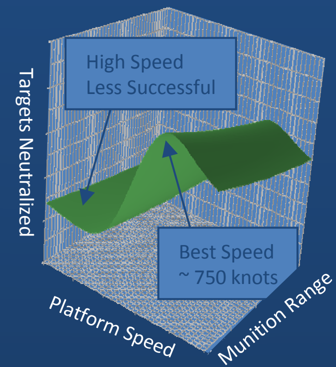


Map Image c/o National Geospatial Intelligence Agency (www.nga.mil



Distribution of Successful Engagements in Iraq (Desert Storm Scenario)

Successful Engagements Favor High Wing Loading and Low Thrust/Weight Ratio (Bomber-like)



The Complexity of the Systems-of-Systems Analysis Problem Often Confounds Analysts

What Is Meant By a Complex System?

- Many contrasting views
  - Biology, Computer Science, Engineering, Economics, etc.
- Complex System: two pertinent definitions
  - A system composed of interconnected parts that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts[1] (Reductionism vs. Holism)
  - A system having many interrelated, interconnected, or interwoven elements and interfaces[2]

Functional Domain \ Physical Domain	Simple	Complex
Simple	**Simple System** Very Predictable. Traditional engineering methods apply.	**Complicated System** Satisfies functional requirements, but cannot ensure under all possible conditions/ states
Complex	**Chaotic System** (Non-Deterministic) Random perturbations give appearance of complexity. Solved using Robust Design	**Complex System** Must architect system to behave correctly by tailoring the emergent behaviors

Figure adapted from Balestrini-Robinson, Santiago. "A Modeling Process to Understand Complex System Architectures," 2009.

- Architecture[3]:
  - Structure of components
  - Relationships (Complex information exchanges, system interfaces, functional interoperation, etc.)
  - Principles & guidelines governing evolution over time

1. Joslyn, C. and Rocha, L. (2000). *Towards Semiotic Agent-Based Models of Socio-Technical Organizations, 2000.*
2. Crawley, Edward. System Architecture – course notes. MIT, 2005.
3. IEEE Std 610.12

Fundamental Properties of a Complex System

1. Self Organization
2. Non-Linear Interactions
3. Adaptation
4. Heterogeneity

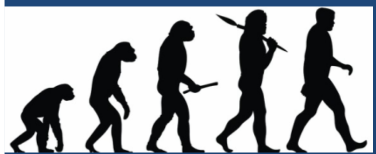
Emergent Behavior

Complex system properties lead to emergent behavior

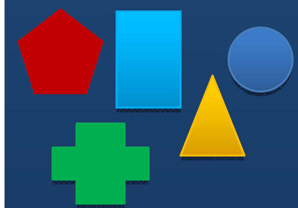
Impact of Complexity on Modeling and Simulation

- Self Organization
  - Feedback and interactions must be captured

- Non-Linearity
  - Behavior is more than sum of the behavior of the components
  - Tiny change in a condition can eventually lead to a huge number of different possible results

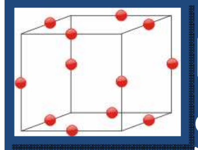


- Adaptation
  - Complex systems continually adapt to their environment to improve performance
  - Adaptive agents are more robust but more difficult to create



- Heterogeneity
  - Chance of emulating emergent behavior increases with more interactions of diverse agents

Enablers for Complex SoS

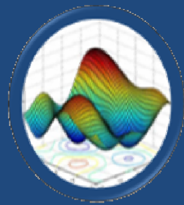


Design of Computer Simulations

- Space Filling Designs
- Adaptive DoE

Modeling and Simulation Techniques

- Agent-based modeling and constructive simulations
- System Dynamics Modeling
- Discrete Event Simulation
- Mathematical Modeling Techniques



Non-linear Surrogate Modeling

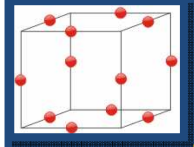
- Neural Networks
- Kriging/Gaussian
- Stepwise RSE

Probabilistic Theory

- Stochastic modeling
- Surrogate modeling of stochastic processes
- Monte Carlo Simulation

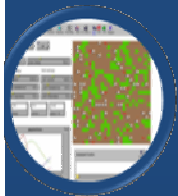
Visual Analytics

Enablers for Complex SoS



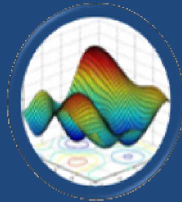
Design of Computer Simulations

- Space Filling Designs
- Adaptive DoE



Modeling and Simulation Techniques

- Agent-based modeling and constructive simulations
- System Dynamics Modeling
- Discrete Event Simulation
- Mathematical Modeling Techniques



Non-linear Surrogate Modeling

- Neural Networks
- Kriging/Gaussian
- Stepwise RSE

Probabilistic Theory

- Stochastic modeling
- Surrogate modeling of stochastic processes
- Monte Carlo Simulation

Visual Analytics

Design of Experiments

- Design of Experiments (DoE) was developed for physical experiments
  - Effect of fertilizers on crops
  - Effect of food and environment on bacteria growth
  - Variations in weld strengths
- Design of Experiments has historically focused on how to devise screening techniques and sampling strategies for physical experiments that are aimed at mitigating the effects of the *random error*

Physical vs. Computational Experiments

Physical Experiments

- Often a limited number of factors
- Data collection must often be done in “one shot” (for example, one growing season)
- Types of Error
  - Human Error: Experimenter makes a mistake
  - Systemic Error: Flaw in philosophy of the experiment adds a consistent bias to result
  - Random Error: Measurement inaccuracies due to the instruments being used

Computational Experiments

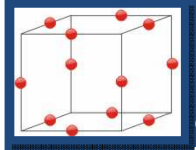
- Often have a larger number of factors than real world experiments
- Data collection is sequential in nature
- Types of Error
  - Human Error: Bugs in the code, incorrectly entered boundary conditions, etc
  - Systemic Error: Consistent errors due to approximations in the code
  - Random Error: Does not exist in computational experiments

Design of Computer Simulation

- Computer simulation is a numerical technique for conducting experiments on certain types of mathematical and logical models describing the behavior of a system (or some component thereof) on a digital computer over extended periods of real time. (Burdick & Naylor, 1966)

- Design of Computer Simulation (DoCS) is geared toward developing sound experimental design practices foe experiments performed on computational simulations

Enablers for Complex SoS

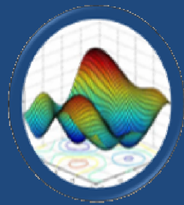


Design of Computer Simulations

- Space Filling Designs
- Adaptive DoE

Modeling and Simulation Techniques

- Agent-based modeling and constructive simulations
- System Dynamics Modeling
- Discrete Event Simulation
- Mathematical Modeling Techniques



Non-linear Surrogate Modeling

- Neural Networks
- Kriging/Gaussian
- Stepwise RSE

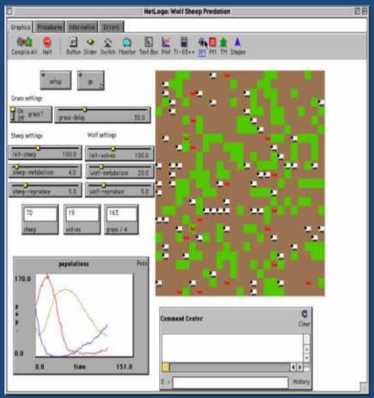
Probabilistic Theory

- Stochastic modeling
- Surrogate modeling of stochastic processes
- Monte Carlo Simulation

Visual Analytics

Agent-Based Behavioral Modeling

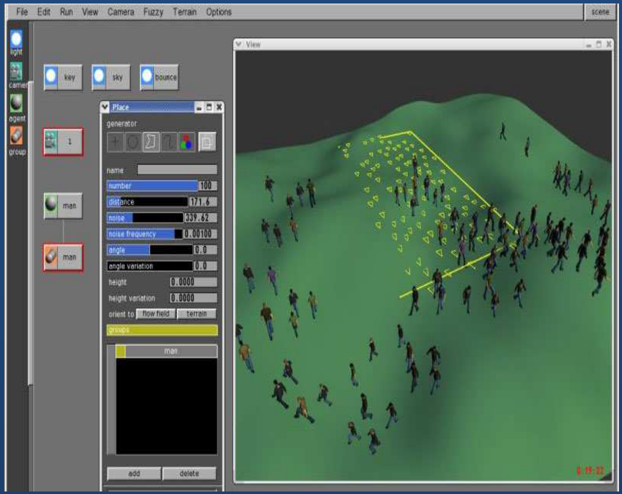
- Agent based modeling (ABM) is a micro-level **bottom-up** approach to modeling phenomena at the entity level in position and time
- Each agent interacts with its environment and with each other
- ABM answers "how properties of the whole emerge from properties of the constituent elements"
  - Behavior of overall stock market arises from the prices of individual stocks bought and sold
  - Scenes of battle in *Lord of the Rings* arise from the simulated behavior of many orcs
- Methods for validation needed



Netlogo Agent-Based Simulation Tool
http://ccl.northwestern.edu/netlogo/

Massive Software
www.massivesoftware.com

Image: http://www.vfxtalk.com/forum/massive-software-used-create-visual-t5617.html



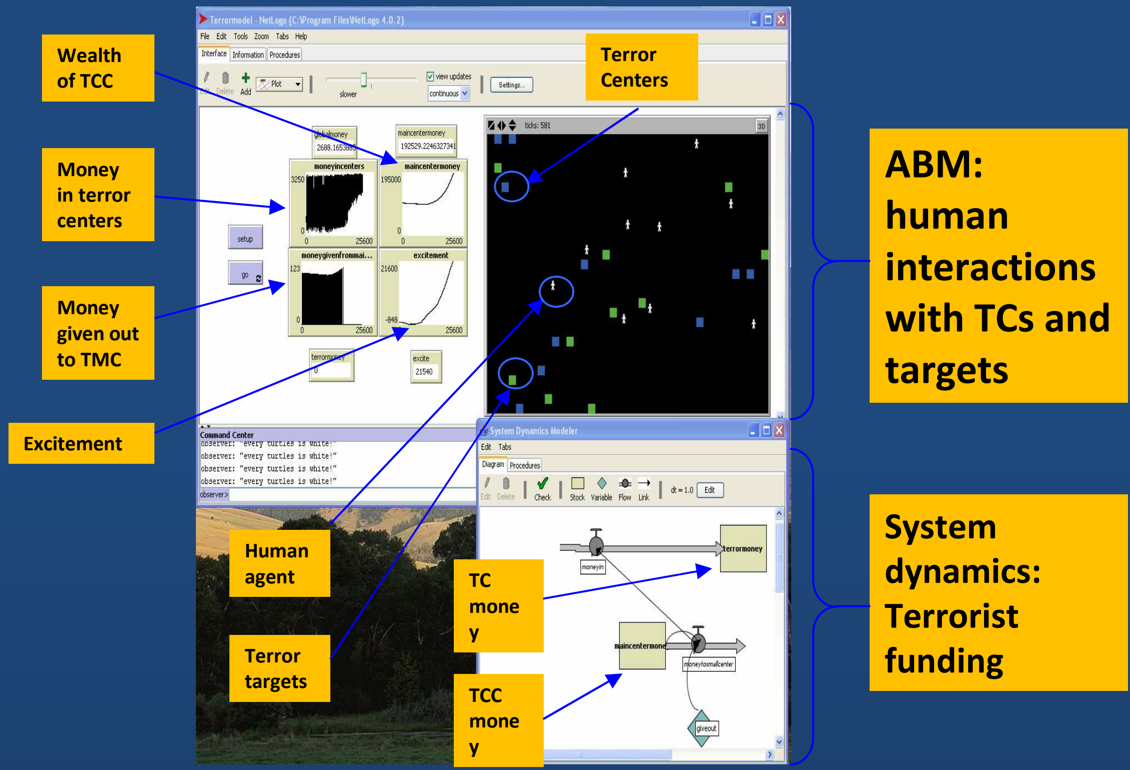
Agent-Based Techniques Model Behaviors with a Bottom-Up Constructionist View

Agent-Based Behavioral Modeling

- Agent Based Models are appropriate when [Bonabeau 2002]:
  - Individual behavior is nonlinear and can be characterized by discrete decisions, thresholds, if-then rules, or nonlinear coupling
  - Describing discontinuity in individual behavior is difficult with differential equations. For example, if a logistics officer orders parts in batches, he may have a threshold for making parts requests (rather than continuously demanding replacements for parts used)
  - History matters. Path-dependence, lagging responses, non-Markovian behavior, or temporal correlations including learning and adaptation are applicable to the system.
  - Averages are not good enough. Under certain conditions, small fluctuations in a complex system can be amplified, so that the system is stable for incremental changes but unstable to large perturbations

System Dynamics Modeling

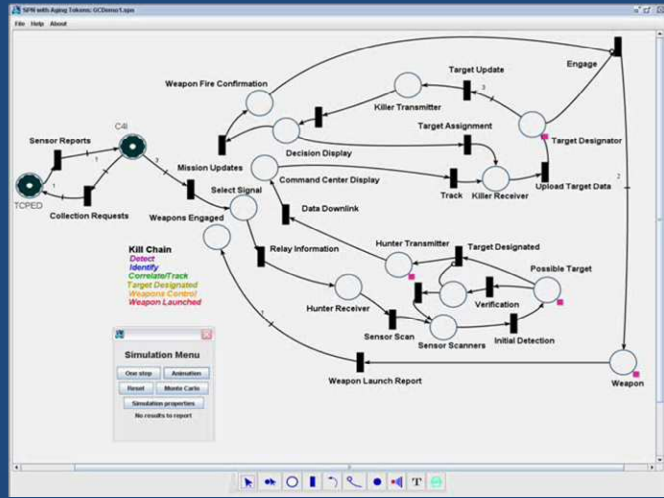
- System Dynamics (SD) is a macro-level **top-down** approach to modeling phenomena at high levels of abstraction and aggregation
- SD models portray the structure of interrelationships between variables with flows and stocks
  - Stocks are the variables in the system
  - Flows represent change
- Methods for rapid model construction and validation are needed

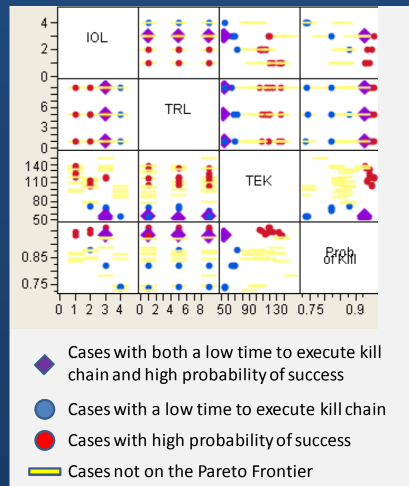


System Dynamics Handles Complexity with a Top-Down View of the World

Discrete Event Simulation

- Discrete Event Simulation (DES) uses numerical analysis to analyze systems where the state variable(s) changes only at discrete points in time
- DES Paradigms
  - Activity Oriented
  - Event Oriented
  - Process Oriented
- DES models have the advantages of a relatively fast run time, flexibility, and modularity
- Useful for modeling queues and logistics



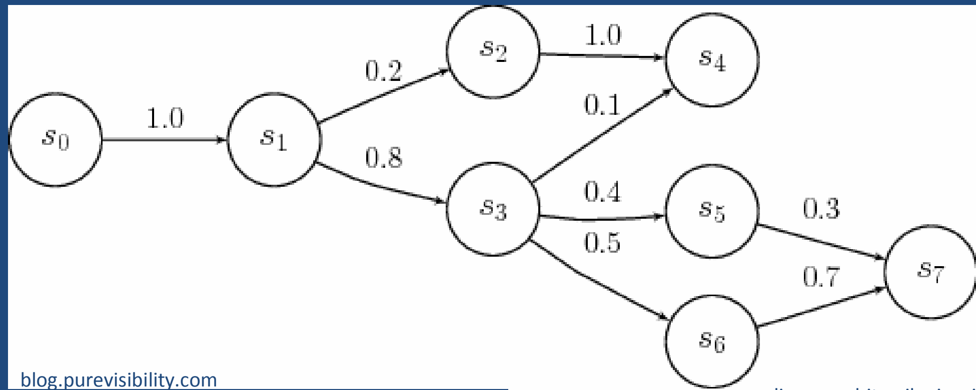


Discrete Event Simulations

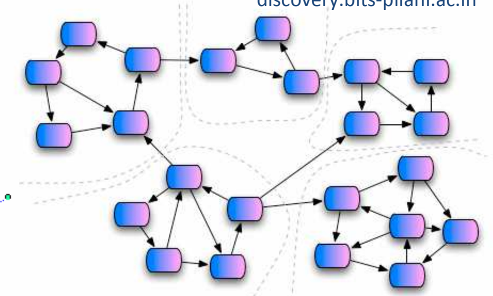
- Discrete event problems embody the following concepts [Fishman 2001]:
  - Work - items, jobs, or customers seeking service
  - Resources - provider of service
  - Routing - collection of required services
  - Buffers - waiting area for work awaiting service
  - Scheduling - pattern of resource availability
  - Sequencing - order resources provide service (e.g. first come first serve)
  - Performance - overall system measure
- DES has many types of applications and describes a broad class of simulations
- Queuing models are able to describe systems with resource allocation and sequences of operations [Zimmermann 2008]

Mathematical Modeling Techniques

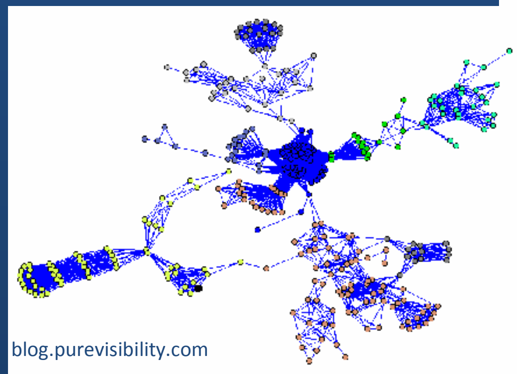
- There are a variety of mathematical modeling techniques that are applicable to SoS
- Markov Chains
  - Used to model stochastic processes which adhere to the Markov Property
- Graph Theory
  - Basis of many network models
  - Can also be used to study the complexity and structure of a SoS



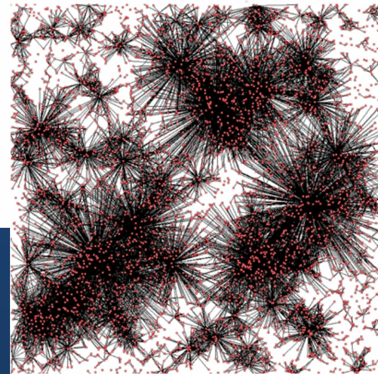
blog.purevisibility.com



discovery.bits-pilani.ac.in

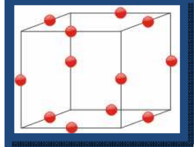


blog.purevisibility.com



Eetimes.com

Enablers for Complex SoS

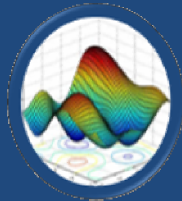


Design of Computer Simulations

- Space Filling Designs
- Adaptive DoE

Modeling and Simulation Techniques

- Agent-based modeling and constructive simulations
- System Dynamics Modeling
- Discrete Event Simulation
- Mathematical Modeling Techniques



Non-linear Surrogate Modeling

- Neural Networks
- Kriging/Gaussian
- Stepwise RSE

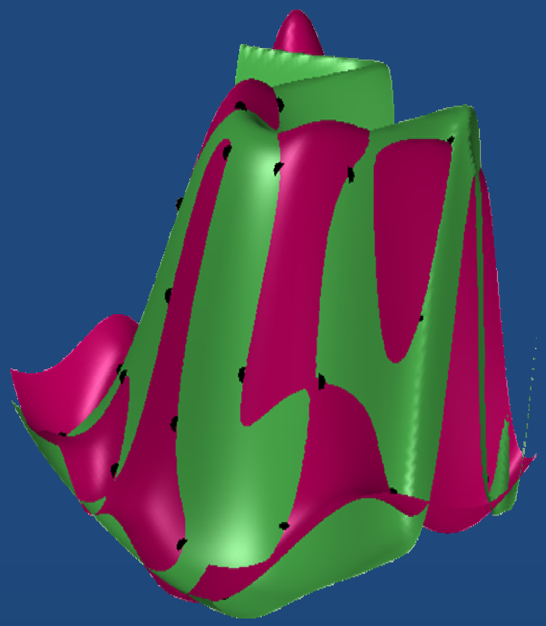
Probabilistic Theory

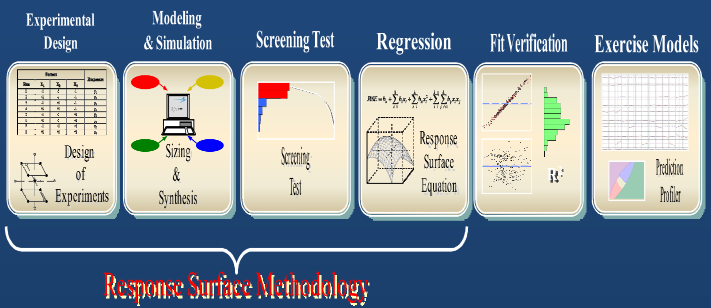
- Stochastic modeling
- Surrogate modeling of stochastic processes
- Monte Carlo Simulation

Visual Analytics

Surrogate Modeling Comes of Age

- In the 1990s, ***surrogate models*** were seen as a mathematical curiosity in the design community
- Response surface equations, Kriging models, and neural networks have been cross-fertilized and their use is now widespread
- Automated tools for creation and validation are needed
- A library of surrogates and the underlying assumptions for their use must be constructed



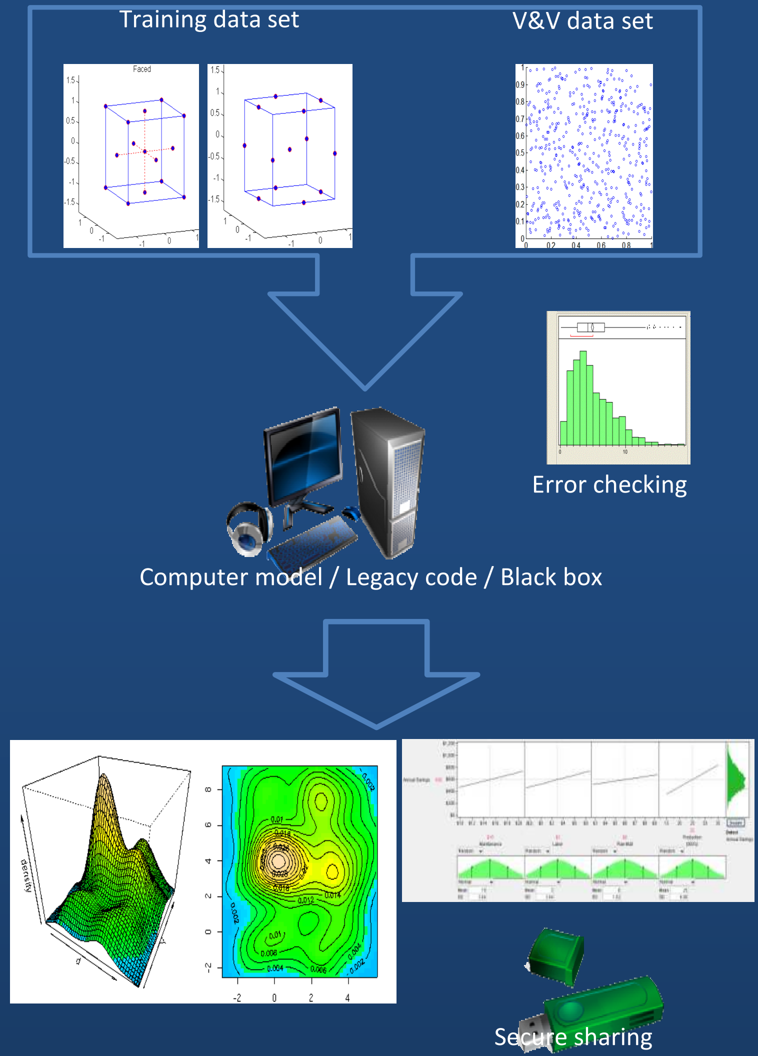


Surrogate modeling for systems analysis is now a standard technique in the field

Surrogate Models

Why do we use surrogate models?

- Statistical analysis of contributing factors, including interactions and high order effects
- Closed-form mathematical characterization of "black box"
- Dynamic / interactive visualization of model space
- Computer evaluation time is multiple orders of magnitude less than legacy "black box" codes, enables Monte Carlo simulations and probabilistic analysis
- Share model of systemic behavior without sharing sensitive tools and models.



What do we need to create surrogate models?

- A carefully selected data set for regression or "training", may imply a significant allocation of resources (Design of Experiments)
- A sufficiently broad data set for Validation & Verification (V&V) through and error checking

Surrogate Models

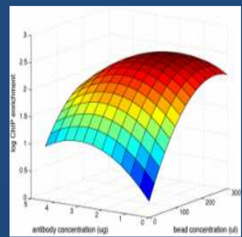
Are surrogate models the silver bullet? No, because:

- They contain statistical error that may be significant
- Their applicability is limited by the domain range of the DoE
- The adequacy of a given surrogate model type depends on the nature of behavior it is meant to capture
- They carry implicit assumptions that can be overlooked

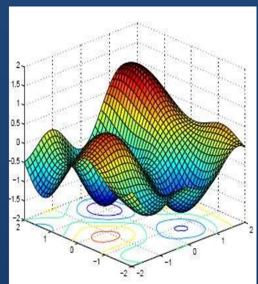
- …altogether, surrogates can be misused or abused for analysis
- Selecting the “right” type of surrogate (validation) is as important as constructing the surrogate “right” (verification)

What kinds of surrogate models are there?

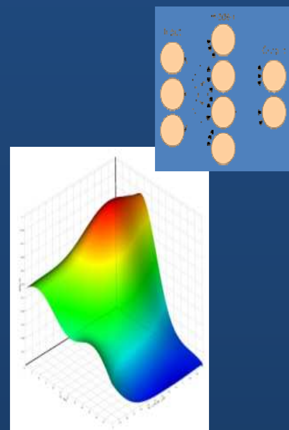
- Different surrogate models will capture varying levels of complex behavior with a given degree of accuracy/error using a corresponding regression/training data set



Response Surface Equations



Gaussian Process Regression, Or Kriging



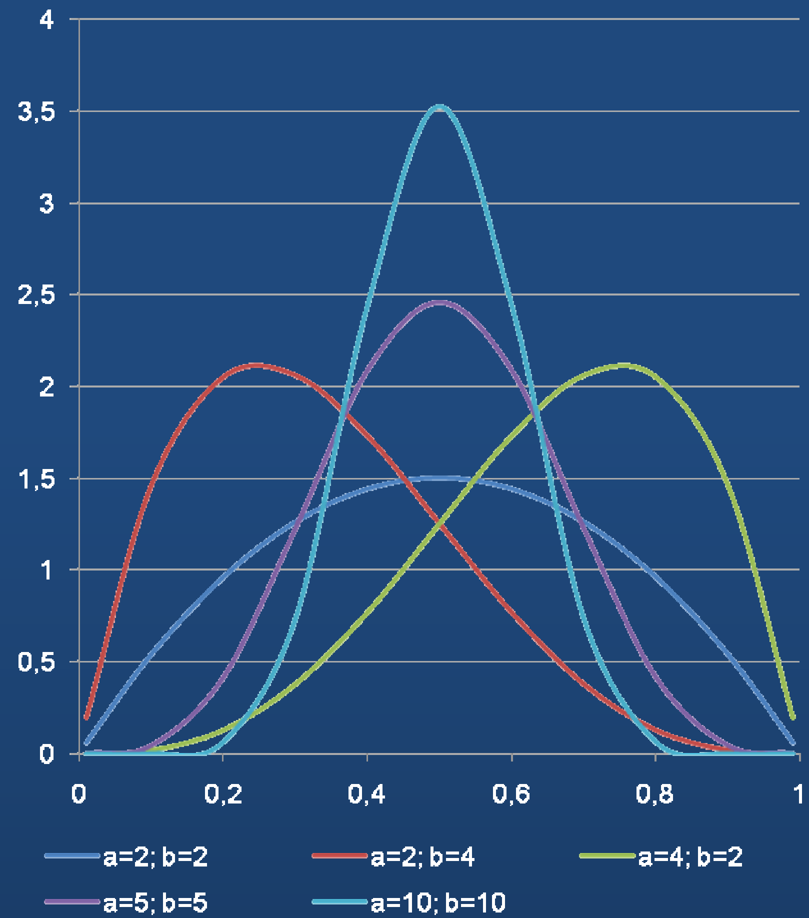
Artificial Neural Networks

Challenges to Surrogate Modeling for Stochastic Processes

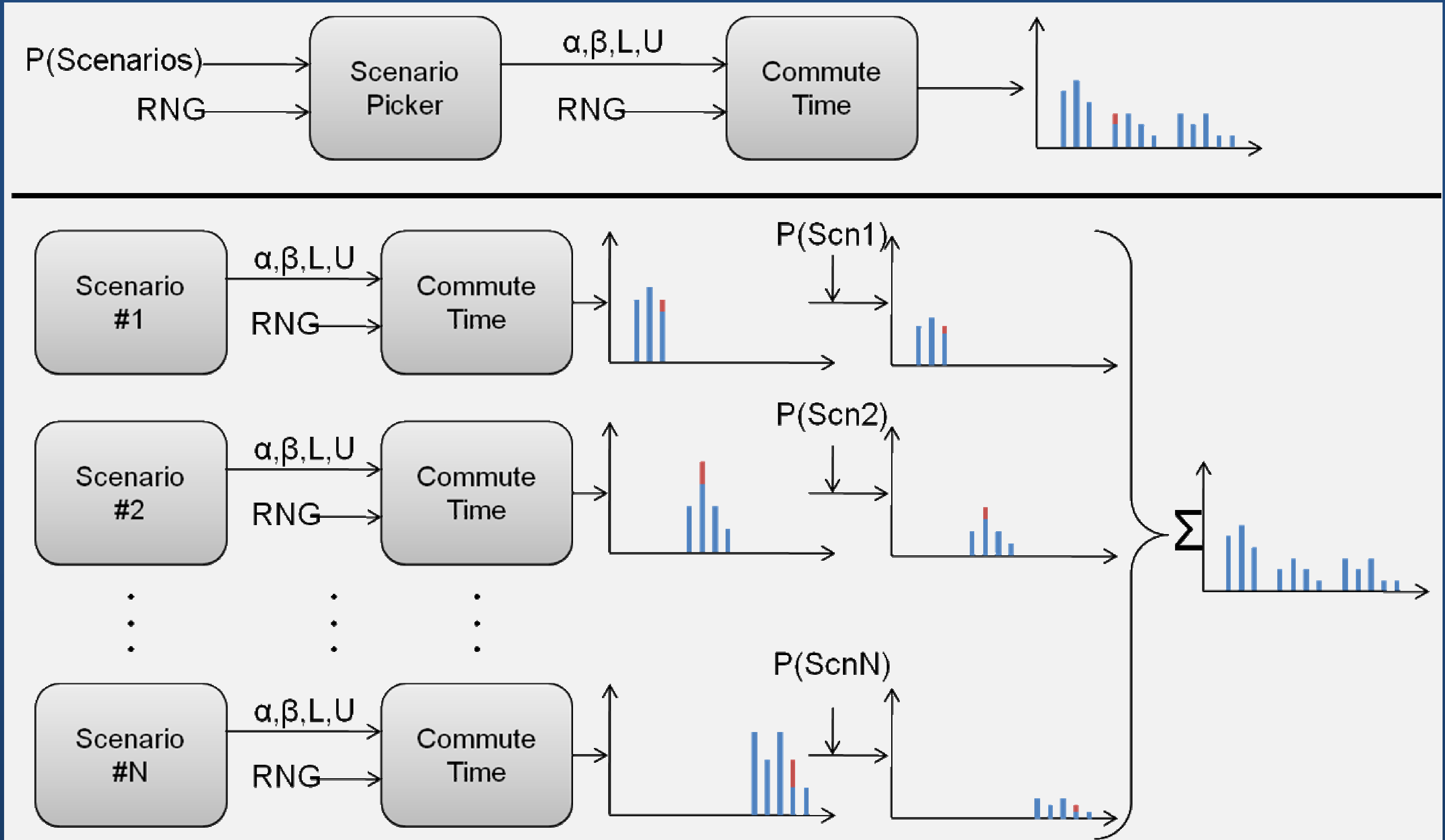
- For a given set of inputs, the outputs are a distribution, not a single point
  - Repetitions of each DoE case are required to capture the distribution
  - If the variability is high, a large number of repetitions are required
- The distribution may be non-normal, or be modal in nature
  - More difficult to accurately model a non-normal distribution
  - In the case of modal behavior, must determine the drivers for the modes
- Multiple surrogates will be required for each response
  - The number of surrogates required will be dependant on the assumed distribution

Surrogate Modeling for Stochastic Processes

- Beta Distribution
  - Beta distributions are extremely flexible functions
  - Beta pdf's have four parameters:
    - α : Shape parameter
    - β : Shape parameter
    - min : Range parameter
    - max : Range parameter



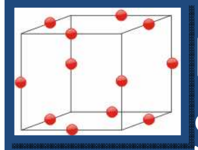
Fitting Modal Responses



Creating Surrogates for Stochastic Models

1. Run a small number of repetitions (10-20) to get an idea of the distribution of the outputs
2. If it appears normal and non-modal, perform a t-test to determine the number of repetitions required for the desired accuracy
3. If it appears non-normal and non-modal, run a t-test to get a ballpark estimate for the number of repetitions, and assume at least a 20% increase in this number will be required
4. If it appears modal, perform testing to determine what factors are driving the modes, and follow the process for fitting surrogates of modal distributions

Enablers for Complex SoS

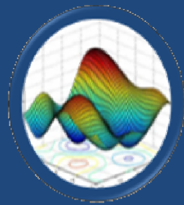


Design of Computer Simulations

- Space Filling Designs
- Adaptive DoE

Modeling and Simulation Techniques

- Agent-based modeling and constructive simulations
- System Dynamics Modeling
- Discrete Event Simulation
- Mathematical Modeling Techniques



Non-linear Surrogate Modeling

- Neural Networks
- Kriging/Gaussian
- Stepwise RSE

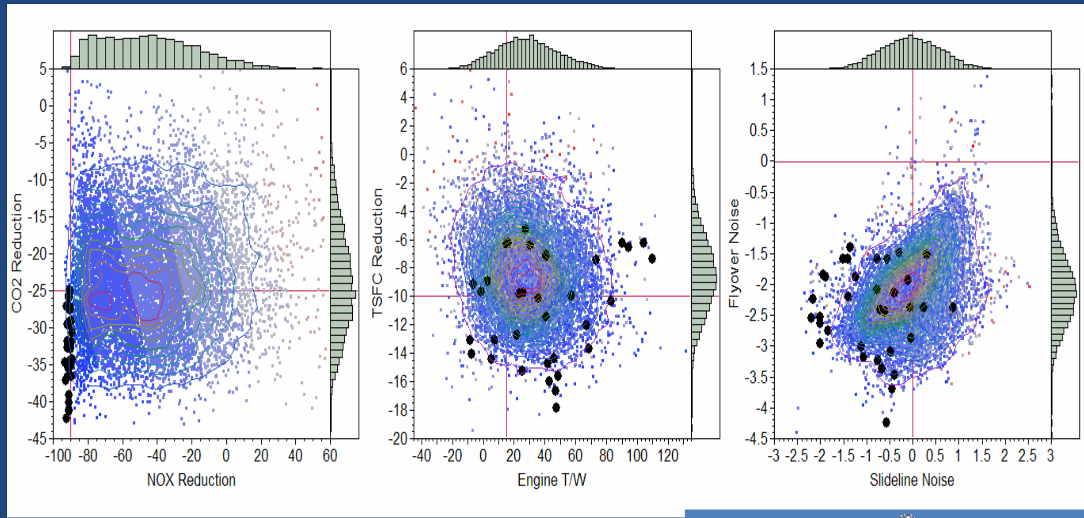
Probabilistic Theory

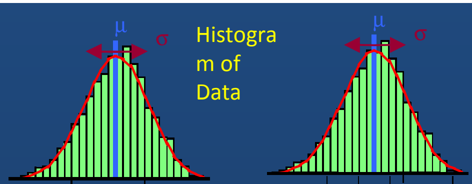
- Stochastic modeling
- Surrogate modeling of stochastic processes
- Monte Carlo Simulation

Visual Analytics

Probabilistic Analysis on Your Desktop

- The use of probability distributions in design applications was once cumbersome and time consuming
- Desktop tools + faster computers make probabilistic techniques affordable and effective for design
- Probabilistic assessments (once beyond reach) provide decision makers with additional information to quantify uncertainty and risk





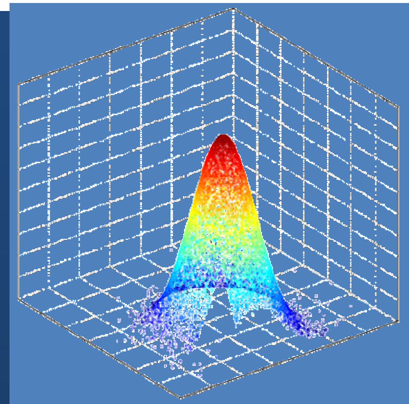
Histogram of Data

Assuming Normal Distributions

μ_{CO2} = -16%
σ_{CO2} = 4.3%

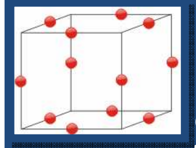
μ_{NOx} = -61%
σ_{NOx} = 19.8%

$$f_{y_1 y_2} = \frac{1}{2\pi\sigma_{y_1}\sigma_{y_2}\sqrt{1-\rho^2}} \exp\left[\frac{1}{2\rho^2-2}\left[\left(\frac{a-\mu_{y_1}}{\sigma_{y_1}}\right)^2 - 2\rho\left(\frac{a-\mu_{y_1}}{\sigma_{y_1}}\right)\left(\frac{b-\mu_{y_2}}{\sigma_{y_2}}\right)+\left(\frac{b-\mu_{y_2}}{\sigma_{y_2}}\right)^2\right]\right]$$



Probabilistic techniques must be applied to all deterministic design tools

Enablers for Complex SoS

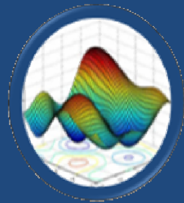


Design of Computer Simulations

- Space Filling Designs
- Adaptive DoE

Modeling and Simulation Techniques

- Agent-based modeling and constructive simulations
- System Dynamics Modeling
- Discrete Event Simulation
- Mathematical Modeling Techniques



Non-linear Surrogate Modeling

- Neural Networks
- Kriging/Gaussian
- Stepwise RSE

Probabilistic Theory

- Stochastic modeling
- Surrogate modeling of stochastic processes
- Monte Carlo Simulation

Visual Analytics

Introduction to Visual Analytics

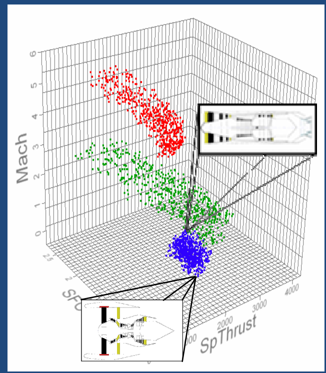
- Challenge: How to analyze overwhelming, disparate, dynamic information

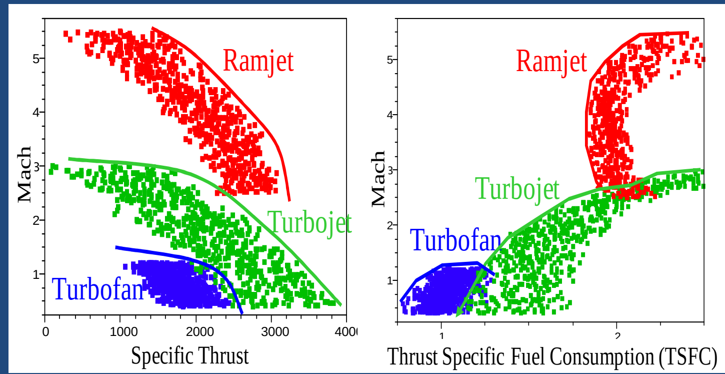
- ***Analytics*** is the "science of analysis" to discover and understand patterns
  - Uses statistical tools and methods
  - Primary goal is to understand the past to predict the future
- ***Visual Analytics*** is "the science of analytical reasoning facilitated by interactive visual interfaces"
  - Provides a mechanism for a user to see an understand large volumes of information at once
  - The brain can best process information received through visual channels
  - Facilitates discovery of unexpected trends and highlights transparency of underlying physical phenomena
- Applications include Homeland Security, marketing, design and optimization, disaster management, and others

Visualization aids decision making for otherwise insurmountable problems, such as those often encountered when working with SoS

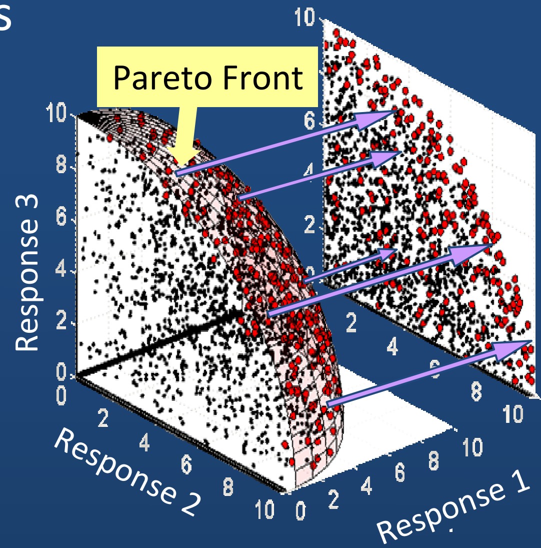
Pareto Optimal Solutions in Many Dimensions

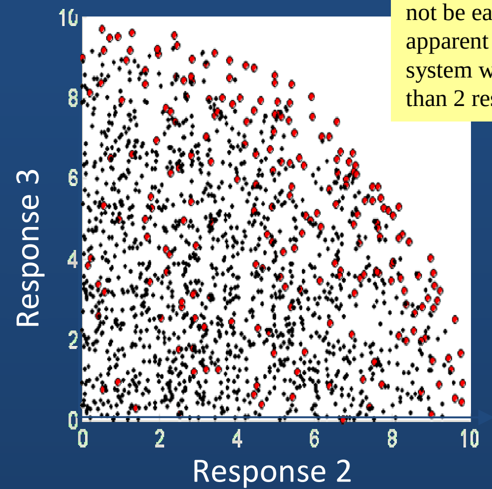
- The use of Genetic Algorithms to find ***Pareto Frontiers*** has become a standard means for multi-objective optimization
- When extended into multiple responses, the concept tends to break down as all solutions
  appear Pareto Optimal
- Methods are needed to slice the design space and visualize
  multidimensional tradeoffs





On a 2-D plot, the Pareto front may not be easily apparent for a system with more than 2 responses.





Visualizing Multi-Dimensional Optimality is Difficult for Human Decision Makers

Multi-Attribute Decision Making

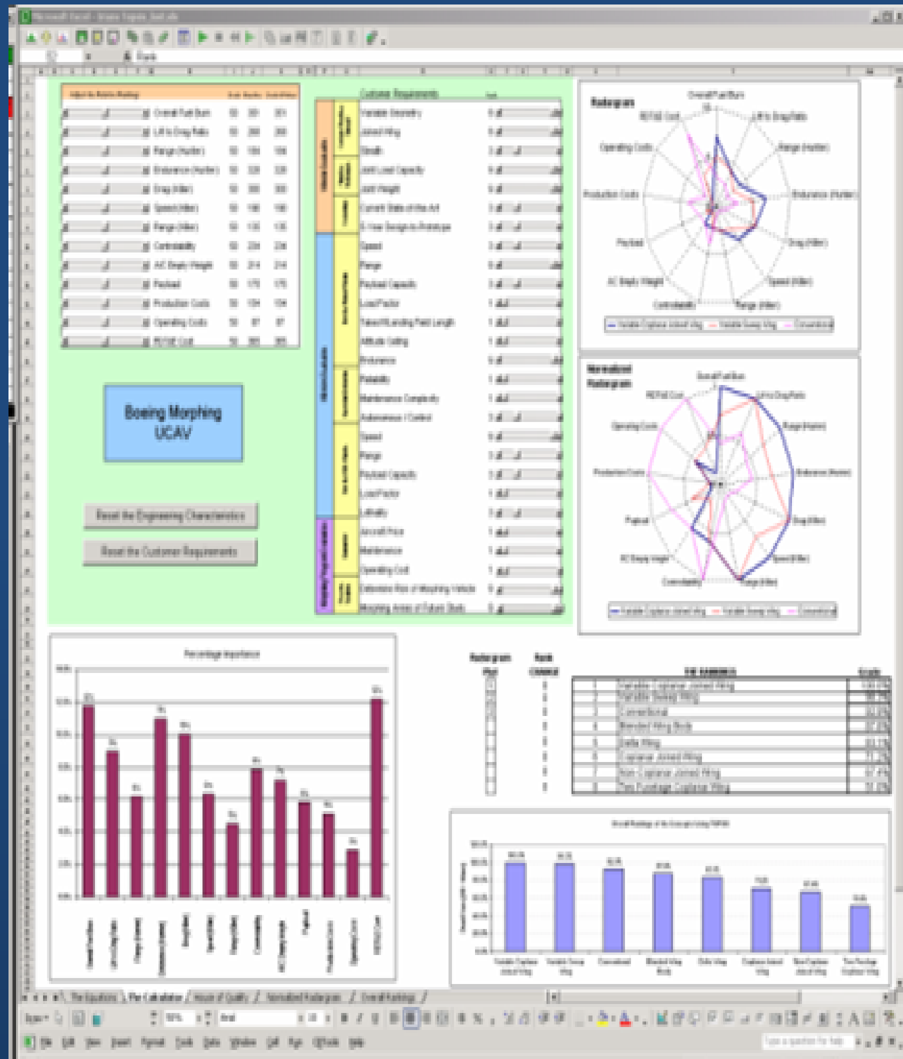
How do we select among a plethora of alternatives in the presence of uncertainty or missing information?

How do we support those making key decisions?

•Multi-Attribute Decision Making techniques provide a mechanism for:

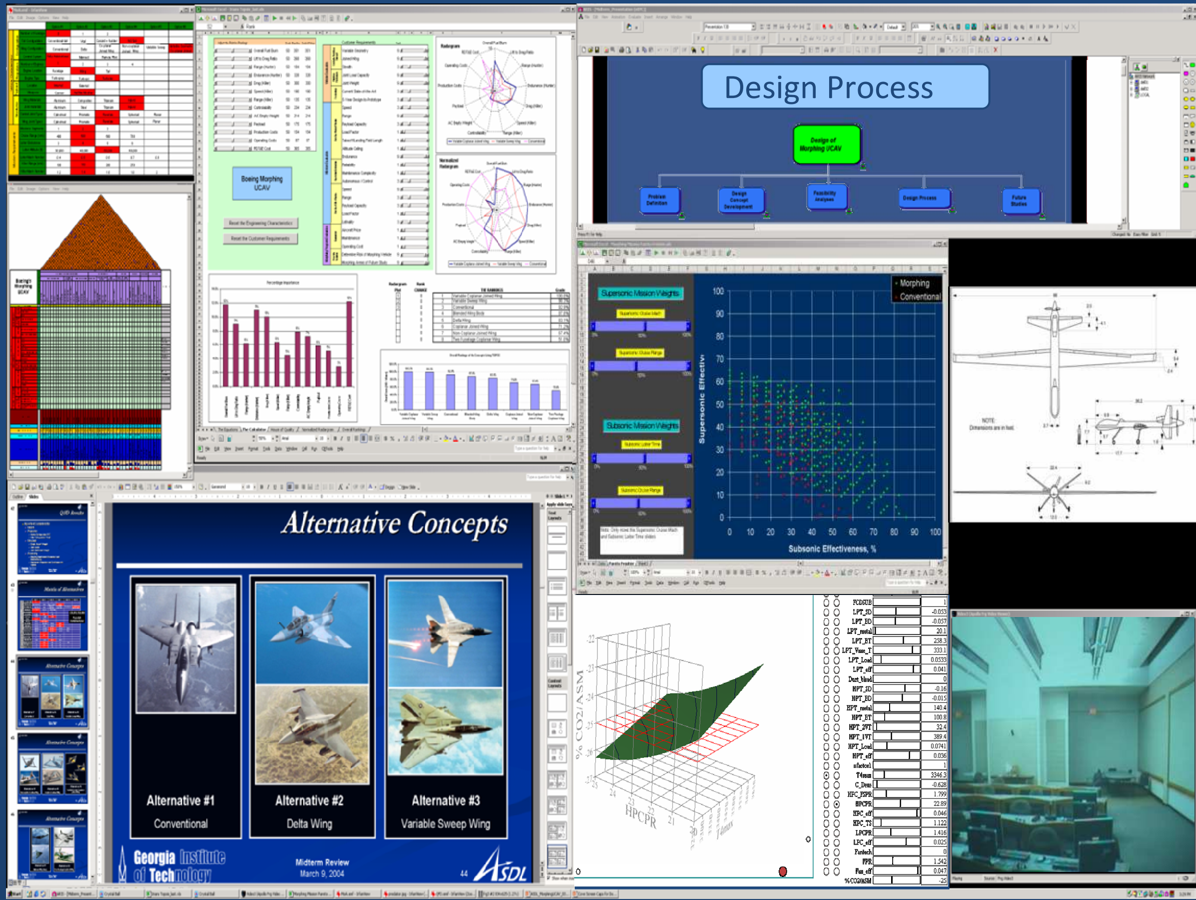
- Structuring information about the alternatives
- Capturing value systems
- Capturing decision-maker preferences
- Scoring alternatives in a traceable and repeatable fashion

•MADM techniques can be readily implemented in interactive, dynamic, and visual environments to support the pre-decisional assessment phase of decision-making



Interactive Electronic Design Reviews

- Interlinking data on a large-format visualization wall allows decision makers to interact with engineers
- Surrogate models, probabilistic techniques, and defined interface standards are required
- The speed of the decision-making/design process is dramatically enhanced



Interactive design reviews are necessary for SoS because of the large amount of information and dynamic nature of trades

Collaboration and Integration in Design

- Design is, by nature, a collaborative endeavor
- Facilities to support integrated design and visualization are becoming more affordable
  - ASDL has the Collaborative Visualization Environment (CoVE) and the Collaborative Design Environment (CoDE)
- Courses that encourage collaboration and the use of new web technologies are needed
- ASDL's Grand Challenges are a used to foster education in collaborative design methods

ASDL's CoVE

ASDL's CoDE

Collaborative Visualization and Design Facilities are Becoming Affordable and Widespread

Collaboration and Integration in SoSE

- Design is, by nature, a collaborative endeavor
- Facilities to support integrated design and visualization are becoming more affordable
- Universities should encourage collaboration and the use of new web technologies
- Design competitions are a good way to foster education in collaborative design methods

Collaborative Visualization Facilities are Becoming Affordable and Widespread

No Shortage of Research Issues and Challenges

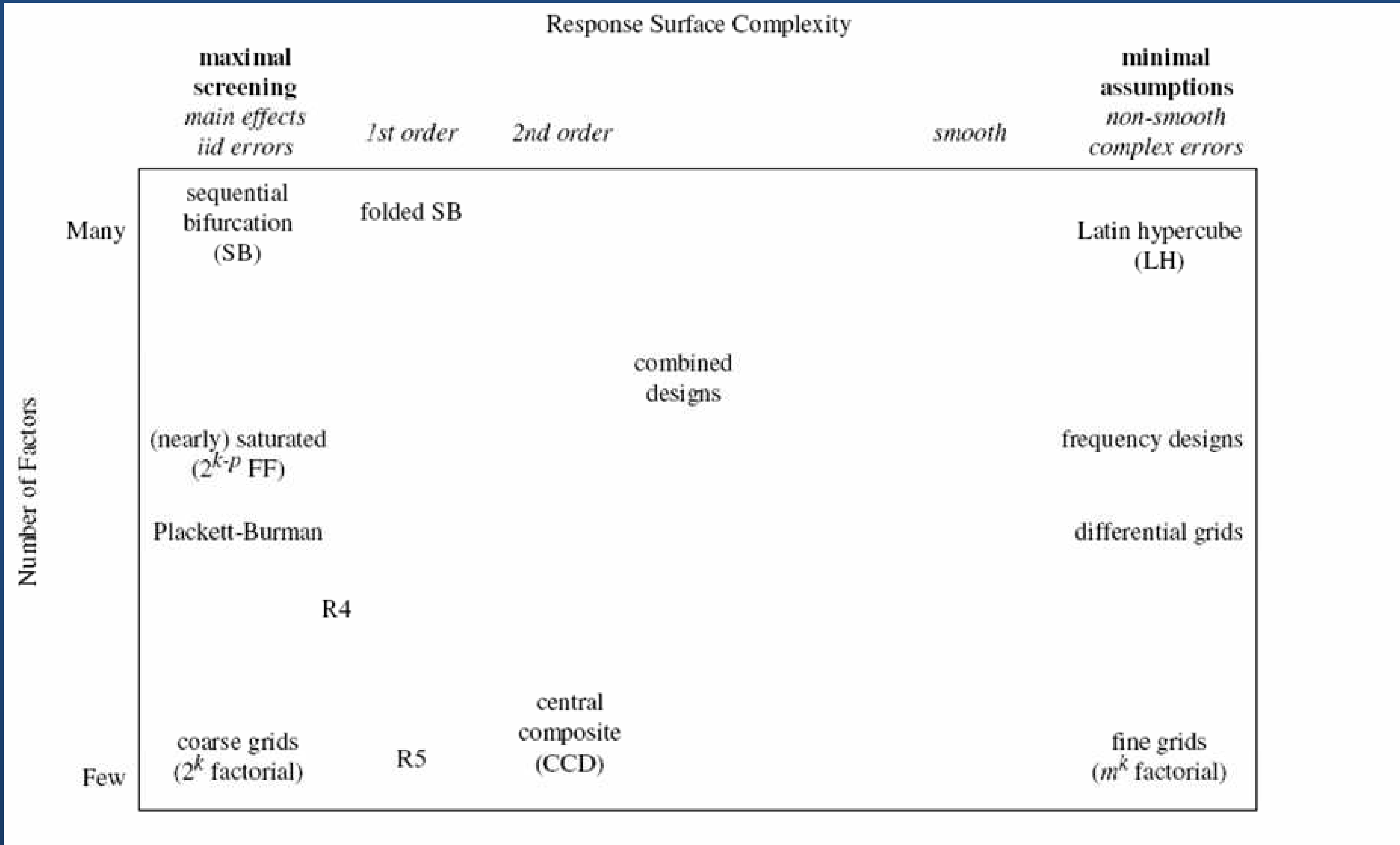
- Limits of Predictability and Controllability
- Time-Varying Dependencies
- Robust vs. Optimal System Designs
- Failure Modes: Graceful Degradation, System Instabilities, Controllability
- Emergent Behaviors and Unpredictable Environments
- Evolvability, Flexibility, and Responsiveness, and the Role of Redundancy
- Characteristics of Complex Systems (Multiple Heterogeneous Systems, Distributed, Not Necessarily Co-Located, Human-Social / Technical Interactions)
- Difficult Decision Making Environments, and the Importance of Human/System Interactions
- Time-Dependent Systems and the Importance of Understanding Network Dynamics
- Operational Independence of Elements
- Managerial Independence of Elements
- Impacts of Policy and Development/ Acquisition Decisions on Readiness and Capability
- Architectures (Distributed, Centralized, Heterogeneous, Hierarchical, Hybrids)
- Experimentation (Component vs. System-Level, Interactions, Emergent Behaviors, Co-Evolution of Technologies, Manned and Unmanned Interactions)
- Modeling and Simulation (Static, Dynamic, Simulation Based Design, Agent-based)
- Energy Integration with Emerging Technologies
- Capability-Based Design Solutions for Robustness to Changing Threat Scenarios
- Metrics (Traditional, Non-Traditional, Quantification of Social Aspects)
- Effective Decision Making (Repercussions, Coupling Techno-Policy- Infrastructure, System & Component Boundaries, Dependencies, Propagation of Information)

Concluding Remarks

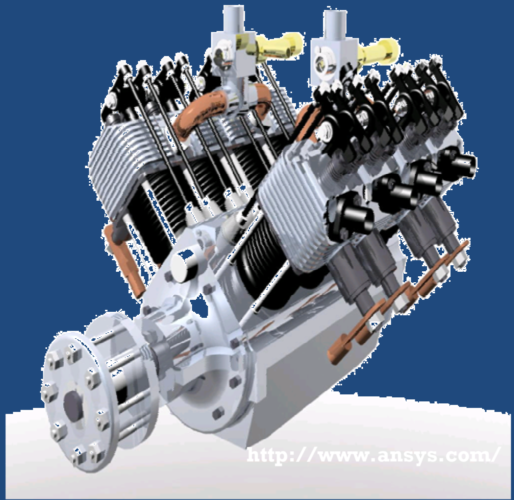
- System of Systems Engineering is a young field with many exciting research opportunities
  - Systems-of-Systems Engineering requires new and novel approaches to improve the traditional SE process
- A wide range of methods is needed in order to address key SoSE challenges in both the military and the civil domain
- Additionally, increased effort is needed in training the next generation of engineers on how to approach problems from an SoS perspective and on the use of collaborative visual analytics design approaches
- Opportunities exist to collaborate under the present ONR study with the Italian Navy on Agent-based Methods with University of Genoa

Questions?

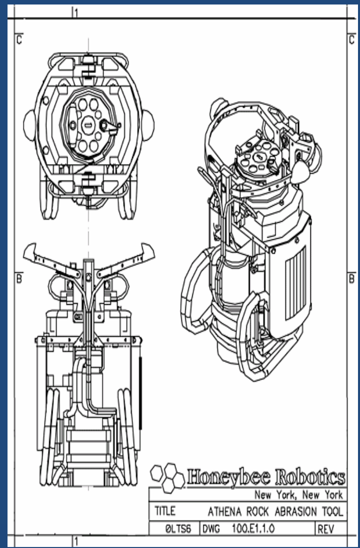
Selecting a Design



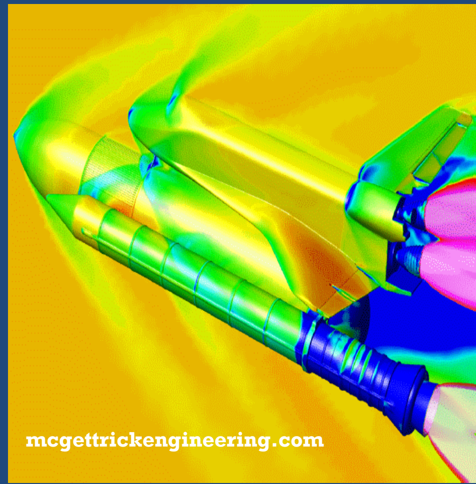
Engineers use many types of models…



CAD Models



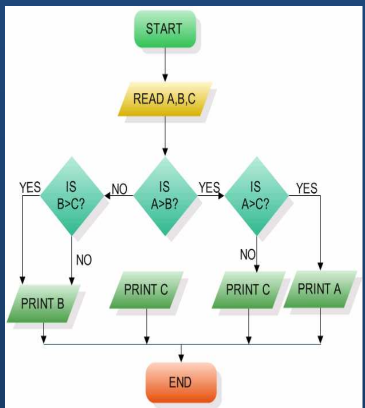
Drawings



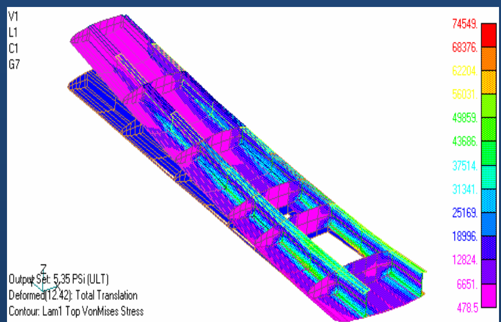
Physics-Based Models

```
Clear[T, U, V, x, y, w, W];
Clear[f, cont];
f[z_] = i (1 - z) / (1 + z);
W = ComplexExpand[f[x + i y]];
U = Together[ComplexExpand[Re[W], TargetFunctions → {Re, Im}]];
V = Together[ComplexExpand[Im[W], TargetFunctions → {Re, Im}]]; ;
T[x_, y_] = 100 - 100/π ArcTan[V/U];
Print["w = ", f[z], " = ", U + i V];
Print[" "];
Print["u = ", U];
Print["v = ", V];
Print[" "];
Print["T[x,y] = 100 - 100/π ArcTan[v/u]"];
Print["T[x,y] = ", T[x, y]];
```

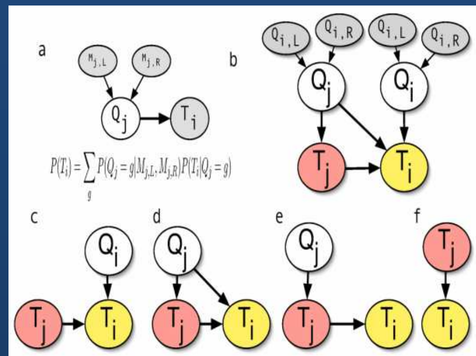
Software Models



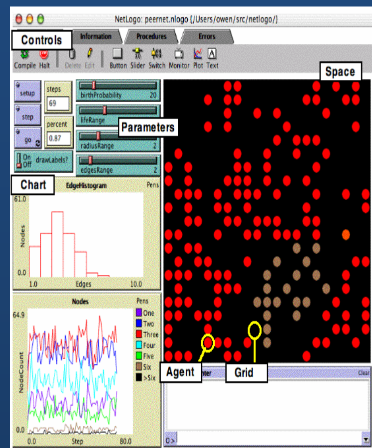
Conceptual Models



Structural Models



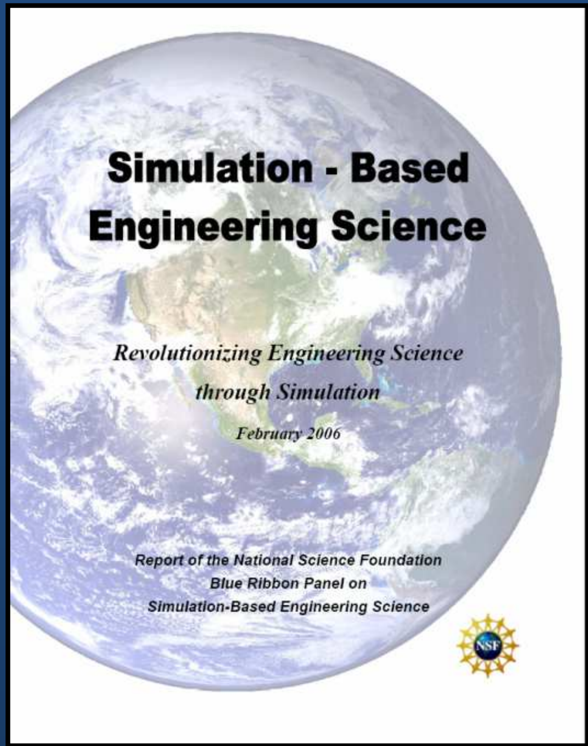
Mathematical Models



Constructive Models

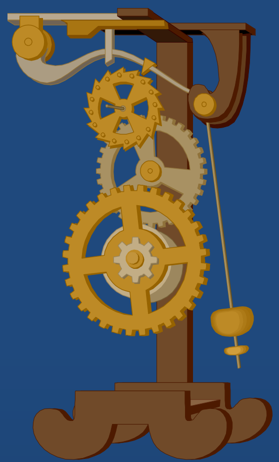
A New Paradigm Shift: Simulation Based Engineering Science

- Numerous expert-opinion-based techniques exist for resource allocation
  - Difficult to extrapolate technology impacts to system-of-systems level where interactions dominate
- Decisions that shape the future of the United States Armed Forces must be enabled by advances in modeling and simulation tools, methods, and techniques [Shelton, 2001]
- According to the NSF Simulation-Based Engineering Science Report (Feb 2006), simulation:
  - "can be used to explore new theories and to design new experiments to test these theories"
  - "also provides a powerful alternative to the techniques of experimental science and observation when phenomena are not observable or when measurements are impractical or too expensive"

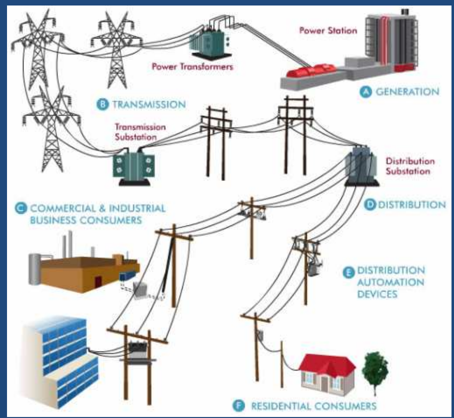


Which of these are systems?

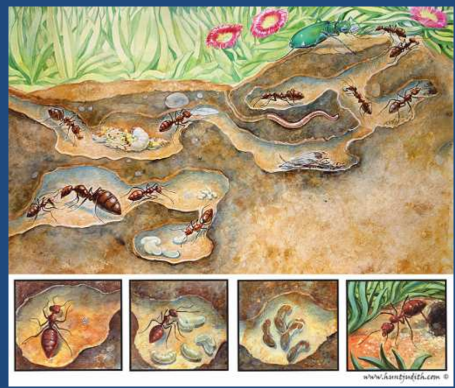
Which are simple? Which are complicated? Which are complex?



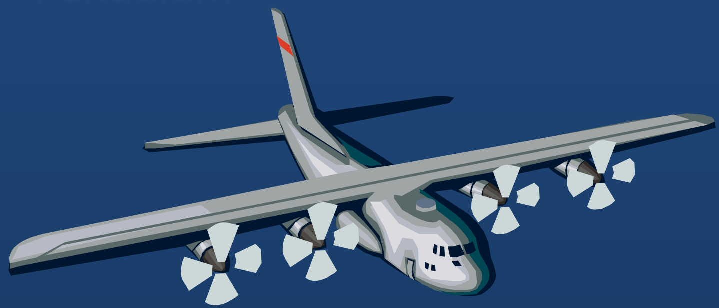
Pendulum



Electricity Grid



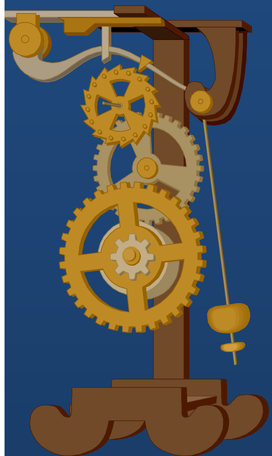
Ant Colony

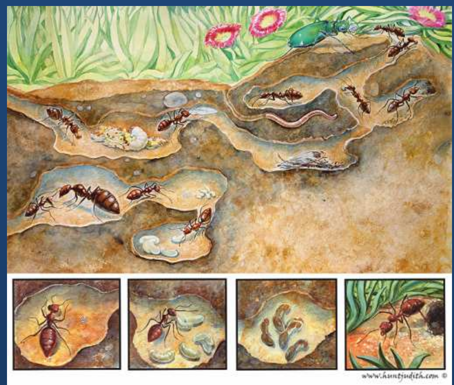


Aircraft

Pen

Which of these are a SoS?





What is a Markov Chain

- Markov Chains are named after AA Markov, who first began studying them in 1907
- A Markov Chain is a mathematical model consisting of a set of states $S=\{s_1,s_2,\ldots s_m\}$ where the probability of transitioning between s_i and s_j at any given time step is p_{ij}, and p_{ij} does not depend on what states have been visited prior to the current time step
  - In other words, the future is dependent only on the present and not on the past
- Markov Property

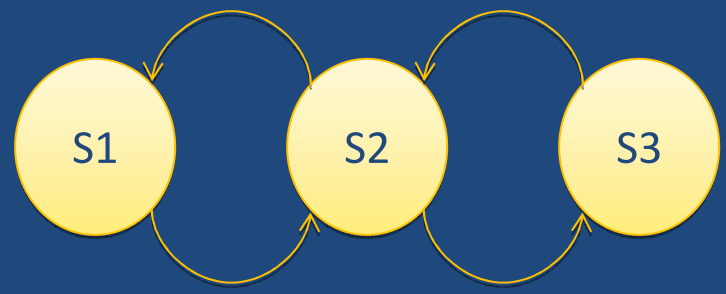
$$P(X_{n+1} = i_{n+1} \mid X_n = i_n, X_{n-1} = i_{n-1}, \ldots, X_0 = i_0) = P(X_{n+1} = i_{n+1} \mid X_n = i_n)$$

Markov Chains

- A Markov Chain is a directed graph in which the edge weights represent transition probabilities, and the probabilities on the edges leaving a vertex sum to 1
- Markov chains are used to model stochastic processes
  - For example, a Markov chain can be used to create a stochastic version of the SIR model developed using system dynamics
  - Queuing models
  - Bacteria growth

Markov Chains

- The transition probability between state i and j is denoted p_{ij}
- They are typically represented in a transition matrix, where the rows represent the present state and the columns represent the state at the next time step



	1	2	3
1	0	p12	0
2	p21	0	p23
3	0	p32	0

Types of Markov Chains

- Time-homogenous
  - Transition probabilities do not vary with time
- Discrete Time
- Branching Process
- Continuous Time
- Poisson Process
  - Special case of CTMC